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Andean surface uplift constrained by radiogenic isotopes of arc lavas

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Climate and tectonics have complex feedback systems which are difficult to resolve and remain controversial. Here we propose a new climate-independent approach to constrain regional Andean surface uplift. $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of Quaternary frontal arc lavas from the Andean Plateau are distinctly crustal (>0.705 and <0.5125 , respectively) which we identify as a plateau discriminant. Strong linear correlations exist between smoothed surface elevation and $^{87}\text{Sr}/^{86}\text{Sr}$ ($R^2=0.858$, $n=17$) and $^{143}\text{Nd}/^{144}\text{Nd}$ ($R^2=0.919$, $n=16$) ratios of non-plateau arc lavas. These relationships are used to constrain 200 Myr of surface uplift history for the Western Cordillera (present elevation 4200 ± 516 m). Between $16\text{--}26^\circ\text{S}$, Miocene to recent arc lavas have comparable isotopic signatures which we infer indicates that current elevations were attained in the Western Cordillera from 23 Ma. From 23-10 Ma, surface uplift gradually propagated southwards by ~ 400 km.

Orogenic plateaux have complex tectonics and variable climates which provide a unique ecological niche. Knowledge of the tectonic evolution and surface uplift of such high, wide regions is fundamental to understanding feedbacks between climate change and tectonics^{1,2}. Orogenic plateaux affect atmospheric circulation and precipitation patterns³. Uplift of high plateaux changes the efficiency of erosion and sediment flux into internal and oceanic basins, leading to atmospheric CO₂ drawdown via silicate weathering and hence long-term global climate cooling^{2,3}. Conversely, arcs erupted through high plateaux emit large quantities of CO₂ during magmatic flare-ups which have been linked to global greenhouse events⁴. Climate-driven aridification and subsequent trench sediment starvation can also focus plate boundary stresses at subduction zones and enhance compressional deformation¹. Despite numerous multidisciplinary studies the topographic, tectonic and geodynamic evolution of orogenic plateaux remains ambiguous^{1,5-7}.

The Andean Plateau is the second-largest tectonically active plateau in the world. From west to east the Andean Plateau spans over 400 km and is divided into three tectonically distinct zones: the Western Cordillera (including the active Central Volcanic Zone, CVZ, of the Andean arc), the internally drained Altiplano and Puna plateaux, and the Eastern Cordillera fold-and-thrust belt (Figure 1). North and south of the plateau Andean arc magmatism continues in the Northern and Southern Volcanic Zones (NVZ and SVZ, respectively) which are separated from the CVZ by two volcanic gaps. Large volumes of Andean arc magmatism have been emplaced along the South American margin since >200 Ma as result of oceanic subduction under the South American continent⁸. During this time the locus of Central Andean arc magmatism has progressively shifted eastward from the modern coastline to its present location^{8,9}.

Many studies have attempted to quantify Andean Plateau surface uplift but most of these works concentrate on regions east of the active arc in the Altiplano, Puna and Eastern Cordillera⁶. Two end-member models of Andean Plateau uplift remain prevalent^{5,6}: slow, steady uplift from at least 40 Ma primarily due to crustal thickening¹⁴⁻²⁰; and rapid, recent surface uplift post 16 Ma as a result of lower lithosphere removal, magmatic thickening or lower crustal flow²¹⁻²⁹. Currently-used paleoelevation proxies, such as paleobotany (refs. 24, 30; and references therein) and stable isotope techniques^{18,21-24}, rely on the assumption that the

dependence of parameters such as air temperature and humidity upon elevation in the past were the same as the present⁶. However, regional climate change related to surface uplift may account for some signals used to interpret elevation gain^{5,31,32}. Paleoclimate conditions are often not corrected for, resulting in large errors on paleoelevation estimates of up to a few kilometers^{31,32}.

Very few studies have constrained paleoelevation estimates for the Western Cordillera⁶. However, geological evidence shows that the Jurassic to Early Cretaceous Andean arc initially developed in an extensional tectonic setting which gradually changed from marine to continental conditions^{14,33}. The onset of compressional deformation in the Western Cordillera between 90-70 Ma is evident from angular unconformities, intrusive relationships and extensive conglomerate deposition in back-arc regions^{17,34}. Deformation and crustal shortening then became diachronous in both the Western and Eastern cordilleras from c. 50-40 Ma^{15,35}. At this time the present high Altiplano-Puna was a ~300 km wide basin close to sea level which separated the two deformation belts^{36,37}. Marked differences in provenance of Late Eocene-Oligocene sediments between basins east and west of the 'Proto'-Western Cordillera provide evidence relief formation at this time³⁸; with further confirmation from facies changes related to uplift dated around ~35 Ma in forearc basins³⁹.

Here we utilize published geochemical and isotopic data for Andean arc lavas to constrain a regional surface uplift history for the Western Cordillera. Arc magma compositions are related to the processes of mantle melting, intra-crustal differentiation and crustal assimilation^{40,41}. It has long been observed that there are links between crustal thickness and certain geochemical parameters of arc lavas^{40,42-44}. Increasing crustal thickness of the overriding plate can affect arc systematics by: reducing the thickness of the mantle wedge, decreasing wedge corner flow and thus limiting the extent of mantle melting^{41,44-46}; raising the pressure of magma fractionation at the Moho and hence changing the stability of certain mineral phases⁴⁷⁻⁴⁹; and increasing the degree of intra-crustal differentiation and crustal assimilation^{40,50,51}. Such links have been utilized to infer crustal thickening in the Central Andes from 40-30 Ma^{14,34,47}. Similarities between chemical and isotopic signatures of Central Andean lavas and middle Cenozoic lavas from the Great Basin in western

67 Utah and Nevada have led to the interpretation that an orogenic plateau was present at this time⁵²,
68 commonly termed the 'Nevadaplano'. Recently, regional and global compilations of geochemical
69 parameters (such as Sr/Y and La/Yb) of both arc and continental collision zone magmatism have been
70 calibrated to modern crustal thickness^{41,45,47-49,53}. Global arc systematics have also been found to correlate
71 with elevation and, assuming isostatic equilibrium², crustal thickness⁵¹. Despite these numerous findings, arc
72 geochemistry has not previously been directly calibrated to elevation and used to infer a regional surface
73 uplift history. Using age corrected Sr- and Nd- isotope ratios we infer that the Western Cordillera was close
74 to current elevations (4200±516 m) by the Early Miocene. From 23-10 Ma, surface uplift propagated
75 southwards through the region of the current volcanic gap and northern SVZ, c. 26-35°S.

76 Results

77 ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd ratios as plateau discriminants

78 ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd ratios are particularly useful in studying interactions between continental crust and
79 depleted mantle, as these reservoirs have a large isotopic contrast (e.g. ref. 40, Figure 2). Qualitative
80 comparisons between ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd ratios of Quaternary Andean arc lavas, crustal thickness and
81 present day topography (Figure 3) confirm previous findings that radiogenic isotopes can be linked to
82 elevation and crustal thickness. Good correlations between present-day surface elevation and crustal
83 thickness along the Andean arc (Supplementary Fig. 1) support the hypothesis of a dominant isostatic
84 control on regional elevation at the arc. Isotope ratios from CVZ (plateau) arc lavas are clearly distinct from
85 either NVZ or SVZ (non-plateau) arc lavas. For example NVZ and SVZ lavas have an arithmetic mean (±2
86 SD) ⁸⁷Sr/⁸⁶Sr ratio of 0.70418 (±0.00036, n=210) and 0.70426 (±0.00098, n=189), respectively, while CVZ
87 lavas have a mean of 0.70671 (±0.00138, n=297). Northern SVZ volcanoes have base elevations over 4000
88 m (Supplementary Figure 2) and are erupted through crust approximately 55 km thick (ref. 13; Figure 3).
89 Such base elevation and crustal thickness values are comparable to CVZ volcanoes from the Andean
90 Plateau, yet baseline isotope ratios from SVZ centres do not overlap with those from the CVZ.

The baseline isotopic signature at each volcanic center is achieved in zones of melting, assimilation, storage and homogenization (MASH) at the base of the crust^{40,50,56,57}. Rising mantle melts experience assimilation of variable amounts of arc crust^{40,50}. CVZ frontal arc lavas are produced by mixing of mantle melts with 7-37% continental crust^{14,50} (Figure 2). To minimize the effect of variable mid- to upper-crustal assimilation and allow direct comparison between different volcanic centres, we define the ‘baseline’ isotope composition at each volcanic centre as the least silicic sample (Figure 4; Methods). CVZ (plateau) lavas have baseline isotopic signatures ($^{87}\text{Sr}/^{86}\text{Sr} > 0.7050$ and $^{143}\text{Nd}/^{144}\text{Nd} < 0.5125$) which are clearly distinct from NVZ and SVZ (non-plateau) lavas over a similar range in SiO_2 content⁵⁰ (Figures 4a,b). Decoupling between isotopic enrichment and major element composition is inferred to reflect prolonged MASH processes in the lower crust⁵⁷. We suggest that this isotopic step change is a result of the tectonic setting varying from a high but narrow arc (northern SVZ and NVZ) to an orogenic plateau (CVZ), as discussed below. Baseline isotope ratios of $^{87}\text{Sr}/^{86}\text{Sr} > 0.7050$ and $^{143}\text{Nd}/^{144}\text{Nd} < 0.5125$ discriminate between plateau and non-plateau settings for Andean arc volcanism.

Correlations between elevation and baseline isotope ratios

Baseline Sr and Nd isotopes of SVZ centres follow strong linear relationships when plotted against both smoothed volcano elevation (Figure 4c, d) and un-smoothed volcano base elevation (Supplementary Fig. 2). Isotope ratios in the SVZ approach CVZ values from south to north. Sr isotope ratios of southern SVZ (SSVZ; south of 38.5°S) lavas are offset to higher values (Figure 4d) which can be attributed to numerous large fracture zones on the incoming Nazca plate which project below the SSVZ⁵⁹. Hydrothermal alteration and serpentinization along these fracture zones increases fluid flux to the mantle wedge, causing a shift to higher $^{87}\text{Sr}/^{86}\text{Sr}$ compositions in the mantle source and in the resultant arc lavas⁵⁹ (Figure 4c). Therefore, we do not include SSVZ volcanoes in our linear regression analysis.

The Central and Southern Andes have pre-Andean basements mostly comprised of Paleozoic accreted terranes intruded by Mesozoic arc plutons^{40,60}. NVZ arc lavas are erupted through a young, accreted oceanic plateau basement of Mesozoic age⁶¹. NVZ lavas have more mantle-like isotopic ratios than SVZ lavas

116 regardless of regional elevation or crustal thickness. For this reason, the NVZ is not included in the same
117 linear regression analysis as SVZ lavas (Figure 4) and we do not attempt a paleoelevation reconstruction for
118 the NVZ. Basements within the CVZ and SVZ produce comparable Sr- and Nd-isotopic shifts for the same
119 degree of crustal contamination if other factors such as the slab parameter and mantle source are
120 equivalent^{40,60}. Geochemical studies indicate the Andean arc front (18-40°S) has tapped a relatively
121 homogenous depleted mantle source since the Jurassic⁵⁵. Back-arc lavas have chemical signatures which
122 indicate a range of mantle sources³³, for this reason we do not include them in our compilation. Therefore
123 our regional paleoelevation estimates only apply to the arc front and present Western Cordillera, not to the
124 back arc regions in the Altiplano-Puna.

125 **Regional surface uplift history for the Western Cordillera**

126 We apply both our plateau discriminant and Sr-isotope paleoelevation proxy to age-corrected pre-
127 Quaternary isotope data ($^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ and $^{143}\text{Nd}/^{144}\text{Nd}_{(i)}$) for the CVZ and SVZ to estimate paleoelevations of
128 the Jurassic-Pliocene Andean arc (~200-2 Ma). We interpret a baseline $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ ratio of >0.7050 and
129 $^{143}\text{Nd}/^{144}\text{Nd}_{(i)}$ ratio of <0.5125 as a 'plateau signature'. We suggest that the isotopic 'plateau signature'
130 corresponds to arc elevations similar to the modern Western Cordillera and CVZ (4200 ± 516 m, mean
131 smoothed elevation of the Western Cordillera along the arc ± 2 SD), but does not correspond to the current
132 width of the entire Andean Plateau. Less radiogenic isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}_{(i)} < 0.7050$,
133 $^{143}\text{Nd}/^{144}\text{Nd}_{(i)} > 0.5125$) are interpreted to correspond to regional elevations according to the linear
134 relationships we have identified for the SVZ (Figures 4c and d). Due to better data coverage of $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$
135 ratios for pre-Quaternary samples we show only our paleoelevation estimates based on Sr isotope
136 compositions. We divide pre-Quaternary radiogenic isotope data into age intervals selected according to the
137 data density (Figure 5), which permits two broad groups for the Miocene-Pliocene (23-10 Ma and 10-2 Ma),
138 but only one each for the Paleogene, Cretaceous and Jurassic periods. Jurassic Central Andean lavas have
139 $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ ratios analogous to the modern southern SVZ, with baseline initial Sr-isotope ratios gradually
140 increasing through the Cretaceous and Paleogene (Figure 5). The largest increase in $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ occurs by ~23

141 Ma (Early Miocene) between 16-26°S where baseline initial isotope ratios reach values $^{87}\text{Sr}/^{86}\text{Sr}_{(i)} > 0.7050$.
142 From 23 to 10 Ma, in the region between 26-33°S there is a gradual increase in $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ from ~ 0.7035 to
143 ~ 0.7050 .

144 Discussion

145 Figure 6 shows our regional paleoelevation estimates for the Andean arc and Western Cordillera compared
146 to previous paleoelevation estimates for the Western Cordillera, Altiplano-Puna and Eastern Cordillera
147 (boxes). A limitation of our method is it will produce over-estimates on paleoelevation where volcanic suites
148 are not analysed or preserved at the least radiogenic end of the range of compositions. We anticipate this
149 issue may only apply to the Jurassic to Paleogene periods for which data are sparse. Jurassic arc baseline
150 compositions and consequent paleoelevation estimates are consistent with geological observations of marine
151 sedimentary rocks intercalated with lavas of that age (ref. 14 and references therein). However, geological
152 evidence suggests that Central Andean basins remained dominantly marine up until the mid-Cretaceous (91
153 Ma)¹⁴, indicating lack of Sr-isotope data for this period are causing overestimates in our elevation model
154 (Figure 6). A marked shift in Central Andean baseline compositions between the Paleogene and Early
155 Miocene indicates an increase in arc elevation of ~ 2 km. Our results suggest that by 23 Ma, between at least
156 16 and 26°S, the Andean arc was part of a tectonic plateau, which we suggest attained elevations
157 comparable to that of the modern Western Cordillera (4200 ± 516 m; Figure 6). Our results do not preclude
158 minor uplift or tilting of the Western Cordillera in the Miocene⁶², as the Western Cordillera could have been
159 at the lower limit of our estimated range at 23 Ma and risen to its current elevations since. The width of
160 elevated areas at this time may have been similar to the modern Western Cordillera (~ 50 -100 km). Such
161 widths are much narrower than the modern Andean Plateau (~ 400 km, which encompasses the Western
162 Cordillera, Altiplano-Puna and Eastern Cordillera), but are wider than either the NVZ or SVZ (mostly
163 < 50 km). This conclusion is consistent with sediment provenience data and facies changes indicating the
164 presence of a 'Proto'-Western Cordillera by the Late Eocene-Oligocene^{38,39}, and also with evidence of
165 eastward propagation of a narrow, early fold-thrust belt into the Eastern Cordillera at ~ 40 Ma^{15,35}. We

166 propose the Western Cordillera was ~2 km higher at 23 Ma than a study from ~15° S (ref. 63) which
167 suggests paleoelevations of ~2 km by 19 Ma (Figure 6). Our result predates rapid Late Miocene (10-6 Ma)
168 surface uplift interpreted for the Altiplano to the east^{22,24}, but is consistent with sediment provenance data
169 which indicates that the Western Cordillera rose earlier than the Altiplano^{38,64}. Our results agree with stable
170 isotope evidence suggesting the south-eastern Puna plateau was at similar to modern elevations by ~36
171 Ma¹⁸. Between 23 and 10 Ma we interpret surface uplift of the Western Cordillera to have propagated
172 further south by ~400 km.

173 Studies on Altiplano paleoelevation have emphasized largescale loss of lower lithosphere as a mechanism
174 for generating rapid surface uplift in this region between 10-6 Ma^{21,22}. Delamination of the lower lithosphere
175 and asthenospheric upwelling results in preferential melting of the most fertile, decompressed or heated
176 mantle⁶⁶. Pliocene-Quaternary back-arc lavas within the Altiplano and Puna have geochemical signatures
177 suggested to be consistent with small scale delamination or dripping⁶⁶⁻⁶⁹, which are not present in the frontal
178 arc to the west¹⁴. Hence, we only calibrate isotope signatures of frontal arc lavas to elevation and our
179 regional paleo-elevation estimates apply only to the (proto-) Western Cordillera.

180 We have identified strong linear correlations between baseline Sr- and Nd-radiogenic isotope compositions
181 of SVZ arc lavas and elevation, and by implication, crustal thickness. Our findings using radiogenic isotope
182 chemistry are complementary to previous studies on relationships between trace element chemistry of arc
183 lavas and crustal thickness^{41,45,47,48}. Crustal thickness of the overriding plate in a subduction zone controls arc
184 lava chemistry by some of, or a combination of all, the following processes: mantle wedge thermal structure
185 and melting regime^{41,44-46}; pressure of magma fractionation at the base of the crust⁴⁷⁻⁴⁹; and the degree of
186 crustal assimilation^{40,50,51}. Correlations between ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd isotopes and SVZ elevation (and
187 crustal thickness) does not preclude either of the first two processes but indicates that there is a relationship
188 between crustal thickness and the degree of crustal assimilation. Therefore, we can indirectly gain an insight
189 on the paleoelevation and tectonic history of the Central Andes using age corrected radiogenic isotope data,
190 which is consistent with the geological record for this region.

191 The slopes of the correlations we have identified here (Figure 4c,d; Supplementary Fig. 2) cannot be directly
192 applied to other arcs. If correlations between Sr- and Nd- isotopes and elevation can be found elsewhere, the
193 slope will depend principally upon the isotopic difference between the mantle source and overriding crust.
194 Our method in determining regional elevation may be applied to other arcs as long as all the steps we have
195 laid out here are followed. There must be an active segment of the arc where Quaternary isotope
196 compositions can be directly correlated to present day elevation. Careful work needs to go into checking arc
197 segments in question to determine if there is reasonable justification to study the elevation (and crustal
198 thickness) control on isotope compositions in isolation. Furthermore, there must be sufficient isotope data
199 available to reliably find the baseline isotope ratio for each volcanic centre. The Central American arc has
200 potential for quantitative relationships between radiogenic isotopes and elevation to be explored further, as
201 qualitative correlations between isotope ratios and crustal thickness have already been found⁴³.

202 The isotopic step change we utilize as a plateau discriminant indicates the relationship between elevation,
203 crustal thickness and isotope composition is not a simple linear trend like that observed for the SVZ (Figures
204 4c,d; ref. 46). The isotopic shift between lavas that are and that are not emplaced on the plateau implies
205 more crustal contamination in CVZ lavas than would be expected from linear extrapolation of the SVZ
206 trend. However, the mechanism for this isotopic enrichment within plateau is relatively unknown and is a
207 topic we highlight as an area of further research. It is possible that the great width (>400 km) of thick (>60
208 km) crust across the Andean Plateau raises the geothermal gradient across this broad region rather than
209 along a narrow arc leading to a hot, weak lower crust⁷. Lower crustal heating due to potential asthenosphere
210 upwelling must also be taken into account^{66,70}.

211 Our approach utilizes abundant radiogenic isotope data from previous studies of Andean arc geochemistry
212 to provide a regional perspective on the surface uplift and tectonic history of the Andes through time.
213 Calibrating radiogenic isotope compositions of arc lavas to smoothed elevation provides a new indirect
214 paleoelevation proxy and plateau discriminant that does not rely on paleoclimate. Miocene (from 23 Ma) to
215 recent Central Andean arc lavas all have a 'plateau' isotope signature ($^{87}\text{Sr}/^{86}\text{Sr} > 0.705$ and

216 $^{143}\text{Nd}/^{144}\text{Nd} < 0.5125$). We suggest that between 16-26°S the Western Cordillera attained current elevations
217 (4200±516 m) by 23 Ma. Our results do not preclude minor tilting or uplift of the Western Cordillera during
218 the Early Miocene. We suggest Western Cordillera elevations were reached ~15 Myr before significant
219 surface uplift previously determined for the adjacent Altiplano to the east. During the Early-Mid Miocene,
220 surface uplift propagated southward between ~26-35°S.

221 **Methods**

222 **Geochemical compilation:** We have compiled a geochemical database for Andean arc lavas, dated from
223 Jurassic to present day, from 41 previously published studies (see Supplementary References 5,9-48). We
224 have not included ignimbrites, plutonic rocks or back-arc lavas in this database. Jurassic centres that are
225 known to have been erupted underwater and hence have isotope signatures which are affected by seawater
226 contamination³³ are not included. So inter-laboratory isotope data can be compared we have made
227 corrections for different standards used (Supplementary Methods 2). The maximum analytical error reported
228 in our compilation is $< \pm 0.00007$ 2σ for Sr isotope ratios and ± 0.00003 2σ for Nd isotope ratios.

229 **Defining baseline isotopic signatures:** Data in Figure 3 (Supplementary Table 2) are isotope ratios of the
230 least silicic sample from each volcanic centre in our compilation. Where major element compositions are
231 not published, we choose the least radiogenic sample for that volcanic centre. We do not include centres
232 with only one sample.

233 **Data availability**

234 All data used in this manuscript are available in Supplementary Tables 1-3. Further queries and information
235 requests should be directed to the lead author Erin M. Scott (erin.scott@durham.ac.uk).

236 **References**

237 1. Lamb, S. & Davis, P. Cenozoic climate change as a possible cause for the rise of the Andes. *Nature*
238 **425**, 792–797 (2003).

- 239 2. Lee, C.-T. A., Thurner, S., Paterson, S. & Cao, W. The rise and fall of continental arcs: Interplays
240 between magmatism, uplift, weathering, and climate. *Earth Planet. Sci. Lett.* **425**, 105–119 (2015).
- 241 3. Armijo, R., Lacassin, R., Coudurier-Curveur, A. & Carrizo, D. Coupled tectonic evolution of
242 Andean orogeny and global climate. *Earth-Sci. Rev.* **143**, 1–35 (2015).
- 243 4. McKenzie, N. R., Hughes, N. C., Gill, B. C. & Myrow, P. M. Plate tectonic influences on
244 Neoproterozoic–early Paleozoic climate and animal evolution. *Geology* **42**, 127–130 (2014).
- 245 5. Barnes, J. B. & Ehlers, T. A. End member models for Andean Plateau uplift. *Earth-Sci. Rev.* **97**, 105–
246 132 (2009).
- 247 6. Garzione, C. N. *et al.* The Tectonic Evolution of the Central Andean Plateau and Geodynamic
248 Implications for the Growth of Plateaus. *Annu. Rev. Earth Planet. Sci.* **45**, (2017).
- 249 7. Jamieson, R. A. & Beaumont, C. On the origin of orogens. *Geol. Soc. Am. Bull.* **125**, 1671–1702
250 (2013).
- 251 8. Coira, B., Davidson, J., Mpodozis, C. & Ramos, V. Tectonic and magmatic evolution of the Andes
252 of northern Argentina and Chile. *Earth-Sci. Rev.* **18**, 303–332 (1982).
- 253 9. Kay, S. M., Burns, W. M., Copeland, P. & Mancilla, O. Upper Cretaceous to Holocene magmatism
254 and evidence for transient Miocene shallowing of the Andean subduction zone under the northern Neuquén
255 Basin. *Geol. Soc. Am. Spec. Pap.* **407**, 19–60 (2006).
- 256 10. Völker, D., Kutterolf, S. & Wehrmann, H. Comparative mass balance of volcanic edifices at the
257 southern volcanic zone of the Andes between 33°S and 46°S. *J. Volcanol. Geotherm. Res.* **205**, 114–129 (2011).
- 258 11. de Silva, S. L. & Francis, P. W. *Volcanoes of the central Andes*. (Springer-Verlag, 1991).
- 259 12. US Geological Survey. GTOPO30 Global Digital Elevation Model. <https://lta.cr.usgs.gov/GTOPO30>
260 (1996).

- 261 13. Assumpção, M., Feng, M., Tassara, A. & Julià, J. Models of crustal thickness for South America
262 from seismic refraction, receiver functions and surface wave tomography. *Tectonophysics* **609**, 82–96 (2013).
- 263 14. Mamani, M., Wörner, G. & Sempere, T. Geochemical variations in igneous rocks of the Central
264 Andean orocline (13°S to 18°S): Tracing crustal thickening and magma generation through time and space.
265 *Geol. Soc. Am. Bull.* **122**, 162–182 (2010).
- 266 15. McQuarrie, N., Horton, B. K., Zandt, G., Beck, S. & DeCelles, P. G. Lithospheric evolution of the
267 Andean fold–thrust belt, Bolivia, and the origin of the central Andean plateau. *Tectonophysics* **399**, 15–37
268 (2005).
- 269 16. Carrapa, B., Strecker, M. R. & Sobel, E. R. Cenozoic orogenic growth in the Central Andes:
270 Evidence from sedimentary rock provenance and apatite fission track thermochronology in the Fiambalá
271 Basin, southernmost Puna Plateau margin (NW Argentina). *Earth Planet. Sci. Lett.* **247**, 82–100 (2006).
- 272 17. Carlotto, V. Paleogeographic and tectonic controls on the evolution of Cenozoic basins in the
273 Altiplano and Western Cordillera of southern Peru. *Tectonophysics* **589**, 195–219 (2013).
- 274 18. Canavan, R. R. *et al.* Early Cenozoic uplift of the Puna Plateau, Central Andes, based on stable
275 isotope paleoaltimetry of hydrated volcanic glass. *Geology* **42**, 447–450 (2014).
- 276 19. Chapman, A. D. *et al.* Constraints on plateau architecture and assembly from deep crustal xenoliths,
277 northern Altiplano (SE Peru). *Geol. Soc. Am. Bull.* **127**, 1777–1797 (2015).
- 278 20. Zhou, R., Schoenbohm, L. M., Sobel, E. R., Davis, D. W. & Glodny, J. New constraints on
279 orogenic models of the southern Central Andean Plateau: Cenozoic basin evolution and bedrock
280 exhumation. *Geol. Soc. Am. Bull.* **129**, 152–170 (2017).
- 281 21. Garzione, C. N., Molnar, P., Libarkin, J. C. & MacFadden, B. J. Rapid late Miocene rise of the
282 Bolivian Altiplano: Evidence for removal of mantle lithosphere. *Earth Planet. Sci. Lett.* **241**, 543–556 (2006).

- 283 22. Garzione, C. N. *et al.* Rise of the Andes. *Science* **320**, 1304–1307 (2008).
- 284 23. Leier, A., McQuarrie, N., Garzione, C. & Eiler, J. Stable isotope evidence for multiple pulses of
285 rapid surface uplift in the Central Andes, Bolivia. *Earth Planet. Sci. Lett.* **371–372**, 49–58 (2013).
- 286 24. Kar, N. *et al.* Rapid regional surface uplift of the northern Altiplano plateau revealed by multiproxy
287 paleoclimate reconstruction. *Earth Planet. Sci. Lett.* **447**, 33–47 (2016).
- 288 25. Garzione, C. N. *et al.* Clumped isotope evidence for diachronous surface cooling of the Altiplano
289 and pulsed surface uplift of the Central Andes. *Earth Planet. Sci. Lett.* **393**, 173–181 (2014).
- 290 26. Schildgen, T. F. *et al.* Quantifying canyon incision and Andean Plateau surface uplift, southwest
291 Peru: A thermochronometer and numerical modeling approach. *J. Geophys. Res. Earth Surf.* **114**, F04014
292 (2009).
- 293 27. Lamb, S. Did shortening in thick crust cause rapid Late Cenozoic uplift in the northern Bolivian
294 Andes? *J. Geol. Soc.* **168**, 1079–1092 (2011).
- 295 28. Lamb, S. Cenozoic uplift of the Central Andes in northern Chile and Bolivia—reconciling
296 paleoaltimetry with the geological evolution. *Can. J. Earth Sci.* **53**, 1227–1245 (2016).
- 297 29. Perkins, J. P. *et al.* Surface uplift in the Central Andes driven by growth of the Altiplano Puna
298 Magma Body. *Nat. Commun.* **7**, 13185 (2016).
- 299 30. Gregory-Wodzicki, K. M., McIntosh, W. C. & Velasquez, K. Climatic and tectonic implications of
300 the late Miocene Jakokkota flora, Bolivian Altiplano. *J. South Am. Earth Sci.* **11**, 533–560 (1998).
- 301 31. Insel, N., Poulsen, C. J., Ehlers, T. A. & Sturm, C. Response of meteoric $\delta^{18}\text{O}$ to surface uplift —
302 Implications for Cenozoic Andean Plateau growth. *Earth Planet. Sci. Lett.* **317–318**, 262–272 (2012).

- 303 32. Fiorella, R. P. *et al.* Spatiotemporal variability of modern precipitation $\delta^{18}\text{O}$ in the central Andes
304 and implications for paleoclimate and paleoaltimetry estimates. *J. Geophys. Res. Atmospheres* **120**, 4630–4656
305 (2015).
- 306 33. Rossel, P., Oliveros, V., Ducea, M. N. & Hernandez, L. Across and along arc geochemical
307 variations in altered volcanic rocks: Evidence from mineral chemistry of Jurassic lavas in northern Chile,
308 and tectonic implications. *Lithos* **239**, 97–113 (2015).
- 309 34. Haschke, M., Siebel, W., Günther, A. & Scheuber, E. Repeated crustal thickening and recycling
310 during the Andean orogeny in north Chile (21°–26°S). *J. Geophys. Res. Solid Earth* **107**, ECV 1-18 (2002).
- 311 35. Oncken, O. *et al.* Deformation of the Central Andean Upper Plate System — Facts, Fiction, and
312 Constraints for Plateau Models. in *The Andes: Active Subduction Orogeny* (eds. Oncken, O. *et al.*) 3–27
313 (Springer Berlin Heidelberg, 2006). doi:10.1007/978-3-540-48684-8_1
- 314 36. Lamb, S. & Hoke, L. Origin of the high plateau in the central Andes, Bolivia, South America.
315 *Tectonics* **16**, 623–649 (1997).
- 316 37. Lamb, S., Hoke, L., Kennan, L. & Dewey, J. Cenozoic evolution of the Central Andes in Bolivia
317 and northern Chile. *Geol. Soc. Lond. Spec. Publ.* **121**, 237–264 (1997).
- 318 38. Wotzlaw, J. F., Decou, A., von Eynatten, H., Wörner, G. & Frei, D. Jurassic to Palaeogene
319 tectono-magmatic evolution of northern Chile and adjacent Bolivia from detrital zircon U-Pb
320 geochronology and heavy mineral provenance. *Terra Nova* **23**, 399–406 (2011).
- 321 39. Decou, A., von Eynatten, H., Dunkl, I., Frei, D. & Wörner, G. Late Eocene to Early Miocene
322 Andean uplift inferred from detrital zircon fission track and U–Pb dating of Cenozoic forearc sediments (15–
323 18°S). *J. South Am. Earth Sci.* **45**, 6–23 (2013).
- 324 40. Hildreth, W. & Moorbath, S. Crustal contributions to arc magmatism in the Andes of Central Chile.
325 *Contrib. Mineral. Petrol.* **98**, 455–489 (1988).

- 326 41. Turner, S. J. & Langmuir, C. H. What processes control the chemical compositions of arc front
327 stratovolcanoes? *Geochem. Geophys. Geosystems* **16**, 1865–1893 (2015).
- 328 42. Leeman, W. P. The influence of crustal structure on compositions of subduction-related magmas. *J.*
329 *Volcanol. Geotherm. Res.* **18**, 561–588 (1983).
- 330 43. Feigenson, M. D. & Carr, M. J. Positively correlated Nd and Sr isotope ratios of lavas from the
331 Central American volcanic front. *Geology* **14**, 79–82 (1986).
- 332 44. Plank, T. & Langmuir, C. H. An evaluation of the global variations in the major element chemistry
333 of arc basalts. *Earth Planet. Sci. Lett.* **90**, 349–370 (1988).
- 334 45. Turner, S. J. & Langmuir, C. H. The global chemical systematics of arc front stratovolcanoes:
335 Evaluating the role of crustal processes. *Earth Planet. Sci. Lett.* **422**, 182–193 (2015).
- 336 46. Turner, S. J., Langmuir, C. H., Katz, R. F., Dungan, M. A. & Escrig, S. Parental arc magma
337 compositions dominantly controlled by mantle-wedge thermal structure. *Nat. Geosci.* **9**, 772–776 (2016).
- 338 47. Profeta, L. *et al.* Quantifying crustal thickness over time in magmatic arcs. *Sci. Rep.* **5**, 17786 (2015).
- 339 48. Chiaradia, M. Crustal thickness control on Sr/Y signatures of recent arc magmas: an Earth scale
340 perspective. *Sci. Rep.* **5**, 8115 (2015).
- 341 49. Chapman, J. B., Ducea, M. N., DeCelles, P. G. & Profeta, L. Tracking changes in crustal thickness
342 during orogenic evolution with Sr/Y: An example from the North American Cordillera. *Geology* **43**, 919–
343 922 (2015).
- 344 50. Davidson, J. P. *et al.* The Nevados de Payachata volcanic region (18°S/69°W, N. Chile) II.
345 Evidence for widespread crustal involvement in Andean magmatism. *Contrib. Mineral. Petrol.* **105**, 412–432
346 (1990).

- 347 51. Farner, M. J. & Lee, C.-T. A. Effects of crustal thickness on magmatic differentiation in subduction
348 zone volcanism: A global study. *Earth Planet. Sci. Lett.* **470**, 96–107 (2017).
- 349 52. Best, M. G. *et al.* The Great Basin Altiplano during the middle Cenozoic ignimbrite flareup: insights
350 from volcanic rocks. *Int. Geol. Rev.* **51**, 589–633 (2009).
- 351 53. Hu, F., Ducea, M. N., Liu, S. & Chapman, J. B. Quantifying Crustal Thickness in Continental
352 Collisional Belts: Global Perspective and a Geologic Application. *Sci. Rep.* **7**, (2017).
- 353 54. Franz, G. *et al.* Crustal Evolution at the Central Andean Continental Margin: a Geochemical
354 Record of Crustal Growth, Recycling and Destruction. in *The Andes: Active Subduction Orogeny* (eds. Oncken,
355 O. *et al.*) 45–64 (Springer Berlin Heidelberg, 2006). doi:10.1007/978-3-540-48684-8_3
- 356 55. Lucassen, F. *et al.* Nd, Pb, and Sr isotope composition of juvenile magmatism in the Mesozoic large
357 magmatic province of northern Chile (18–27°S): indications for a uniform subarc mantle. *Contrib. Mineral.
358 Petrol.* **152**, 571–589 (2006).
- 359 56. Freymuth, H., Brandmeier, M. & Wörner, G. The origin and crust/mantle mass balance of Central
360 Andean ignimbrite magmatism constrained by oxygen and strontium isotopes and erupted volumes. *Contrib.
361 Mineral. Petrol.* **169**, 58 (2015).
- 362 57. Walker, B. A., Bergantz, G. W., Otamendi, J. E., Ducea, M. N. & Cristofolini, E. A. A MASH
363 Zone Revealed: the Mafic Complex of the Sierra Valle Fértil. *J. Petrol.* **56**, 1863–1896 (2015).
- 364 58. Farr, T. G. *et al.* The Shuttle Radar Topography Mission. *Rev. Geophys.* **45**, RG2004 (2007).
- 365 59. Jacques, G. *et al.* Geochemical variations in the Central Southern Volcanic Zone, Chile (38–43°S):
366 The role of fluids in generating arc magmas. *Chem. Geol.* **371**, 27–45 (2014).
- 367 60. Mamani, M., Tassara, A. & Wörner, G. Composition and structural control of crustal domains in
368 the central Andes. *Geochem. Geophys. Geosystems* **9**, Q03006 (2008).

- 369 61. Chiaradia, M. Adakite-like magmas from fractional crystallization and melting-assimilation of mafic
370 lower crust (Eocene Macuchi arc, Western Cordillera, Ecuador). *Chem. Geol.* **265**, 468–487 (2009).
- 371 62. Jordan, T. E. *et al.* Uplift of the Altiplano-Puna plateau: A view from the west. *Tectonics* **29**, TC5007
372 (2010).
- 373 63. Saylor, J. E. & Horton, B. K. Nonuniform surface uplift of the Andean plateau revealed by
374 deuterium isotopes in Miocene volcanic glass from southern Peru. *Earth Planet. Sci. Lett.* **387**, 120–131
375 (2014).
- 376 64. Horton, B. K., Hampton, B. A. & Waanders, G. L. Paleogene synorogenic sedimentation in the
377 Altiplano plateau and implications for initial mountain building in the central Andes. *Geol. Soc. Am. Bull.*
378 **113**, 1387–1400 (2001).
- 379 65. Cooper, F. J. *et al.* Aridity-induced Miocene canyon incision in the Central Andes. *Geology* **44**, 675–
380 678 (2016).
- 381 66. Ducea, M. N., Seclaman, A. C., Murray, K. E., Jianu, D. & Schoenbohm, L. M. Mantle-drip
382 magmatism beneath the Altiplano-Puna plateau, central Andes. *Geology* **41**, 915–918 (2013).
- 383 67. Kay, S. M., Coira, B. & Viramonte, J. Young mafic back arc volcanic rocks as indicators of
384 continental lithospheric delamination beneath the Argentine Puna Plateau, central Andes. *J. Geophys. Res.*
385 *Solid Earth* **99**, 24323–24339 (1994).
- 386 68. Davidson, J. P. & Silva, S. L. de. Late Cenozoic magmatism of the Bolivian Altiplano. *Contrib.*
387 *Mineral. Petrol.* **119**, 387–408 (1995).
- 388 69. Kaislaniemi, L., Hunen, J. van, Allen, M. B. & Neill, I. Sublithospheric small-scale convection—A
389 mechanism for collision zone magmatism. *Geology* **42**, 291–294 (2014).

390 70. Kay, S. M., Mpodozis, C. & Gardeweg, M. Magma sources and tectonic setting of Central Andean
391 andesites (25.5–28°S) related to crustal thickening, forearc subduction erosion and delamination. *Geol. Soc.*
392 *Lond. Spec. Publ.* **385**, 303–334 (2014).

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400 **Author Contributions**

401 MBA and EMS were responsible for initial ideas that motivated this manuscript. EMS carried out data
402 acquisition and analysis alongside help, guidance and expertise of all authors. EMS and CS worked on
403 statistical tests. The manuscript was written by EMS with contribution from all authors.

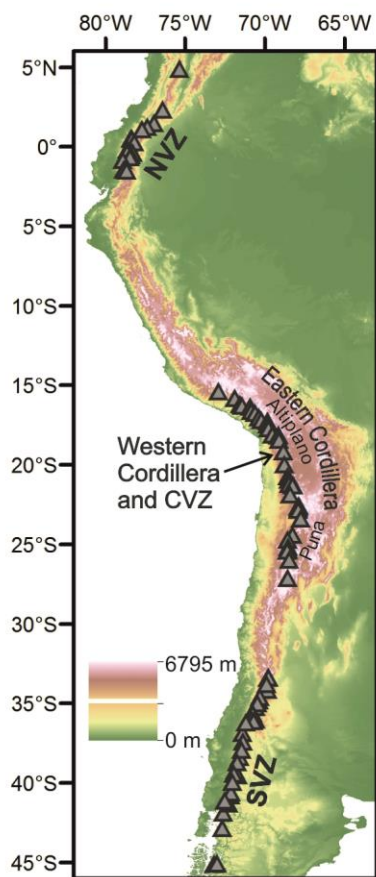
404 **Competing financial interests**

405 To our knowledge, no competing financial interests exist.

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410 **Figure 1 | Topographic map of western South America.** Grey triangles are locations of Holocene arc front
 411 volcanoes from the N, C & SVZ (North, Central and Southern Volcanic Zones) included in our geochemical
 412 compilation (Methods). CVZ centres are located in the Western Cordillera of the Andean Plateau.

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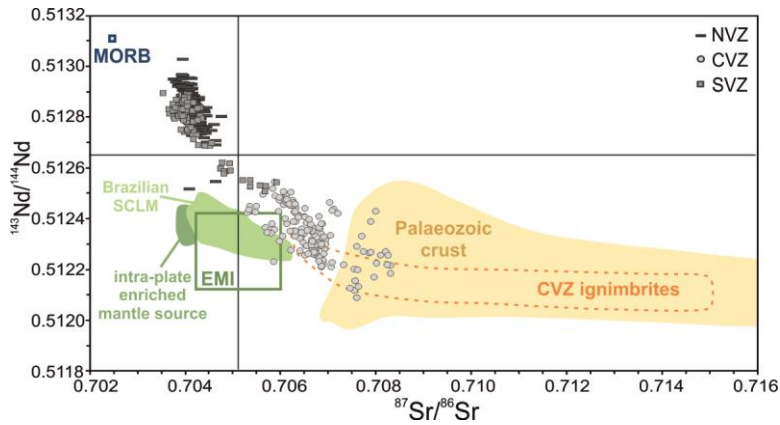


Figure 2 | Andean lavas are produced by mixing of depleted mantle melts with radiogenic crust. Sr-Nd radiogenic isotope plot of Quaternary lavas from the N, C & SVZ (compilation from this study) and CVZ ignimbrites⁵⁴ in comparison to Paleozoic continental crust and mantle end members including Depleted Mantle (Pacific MORB), enriched sub-continental lithospheric mantle (SCLM) and Enriched Mantle I (EMI); from ref. 55 and references therein. Andean frontal arc lavas follow a trend from a depleted mantle source to Palaeozoic crust and are not thought to be influenced by enriched mantle sources⁵⁵.

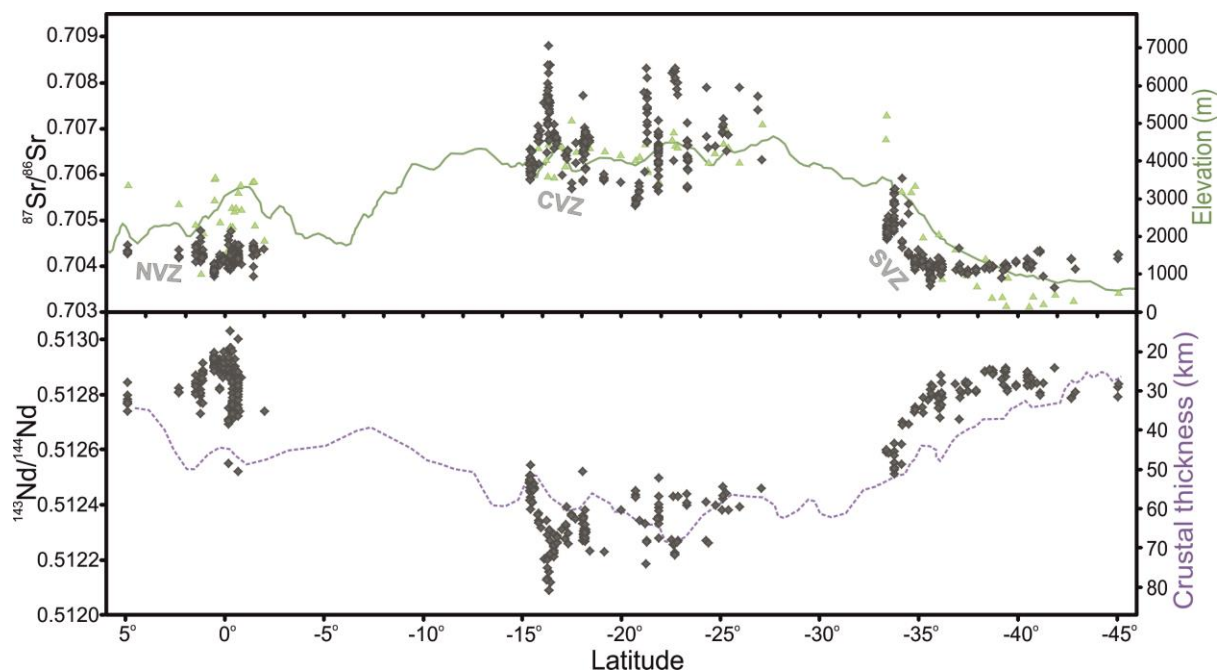


Figure 3 | Comparison of whole rock $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of arc lavas with crustal thickness and elevation. Quaternary whole-rock Sr- and Nd- isotope ratios of frontal arc lavas (diamonds, compilation from this study; see Methods and Supplementary Table 1) compared to volcano base elevation (triangles; this study and refs 10,11), arc front mean elevation (100 km wide swath, GTOPO30 digital elevation model (DEM), ref. 12) and crustal thickness profiles (5 period moving average, data from ref. 13, RMS <3.5 km).

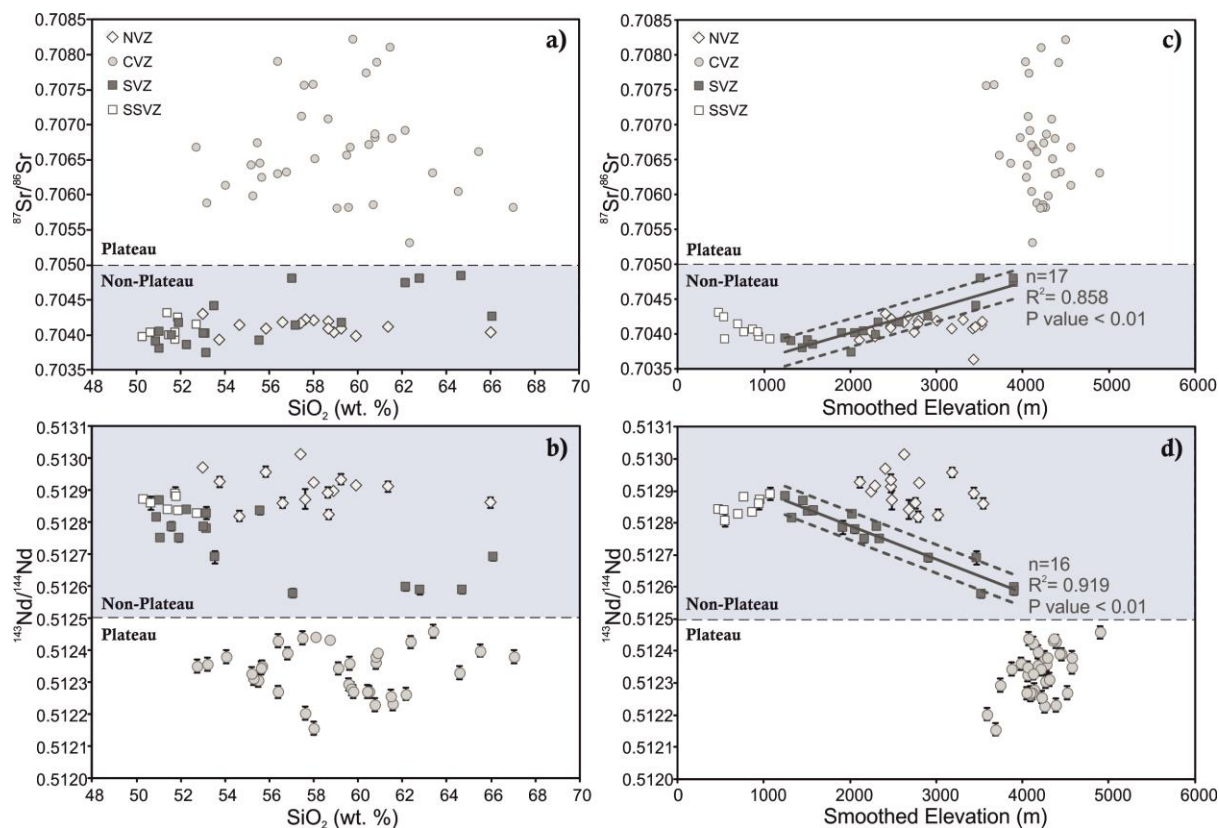


Figure 4 | Baseline Sr- and Nd- isotopes as a plateau discriminant and paleoelevation proxy. (a) and (b)

Baseline isotopic compositions within each volcanic zone vary little with differentiation from basaltic andesite to rhyolite⁵⁰; even the least silicic CVZ rocks are enriched in $^{87}\text{Sr}/^{86}\text{Sr}$ (>0.7050) and depleted in $^{143}\text{Nd}/^{144}\text{Nd}$ (<0.5125). (c) and (d) Baseline isotope compositions compared to smoothed elevation. Elevation smoothed to a radius of 37.5 km was calculated from the Shuttle Radar Topography Mission DEM (SRTM1, pixel resolution 90 m; ref. 58). A radius of 37.5 km is selected as this is half of the maximum crustal thickness in the Andes. Smoothing to this degree filters out non-isostatic, short wave-length topography. 95% confidence intervals are represented as dashed lines (excluding samples south of 38.5°S , see text). Volcano locations are shown on Fig.1a. Symbols are bigger than the maximum analytical error isotope on isotope data, except where shown. Typical quoted analytical precision on SiO_2 compositions are $\sim 3\%$ RSD. All data are listed in Supplementary Table 2.

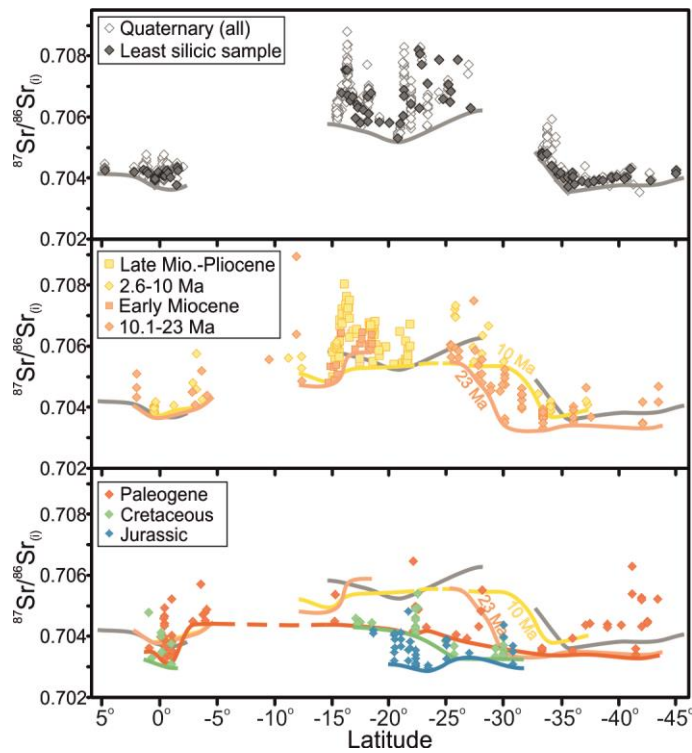


Figure 5 | Evolution of Andean arc initial Sr-isotope compositions from the Jurassic to present. Age corrected Sr-isotope ratios of arc lavas (compilation of this study, Supplementary Table 3) grouped by age show the gradual increase in $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ with time. Baselines are drawn joining minimum values for each age group. Symbols are bigger than the maximum analytical error. For distribution of CVZ analyses versus age, please see Supplementary Fig. 3.

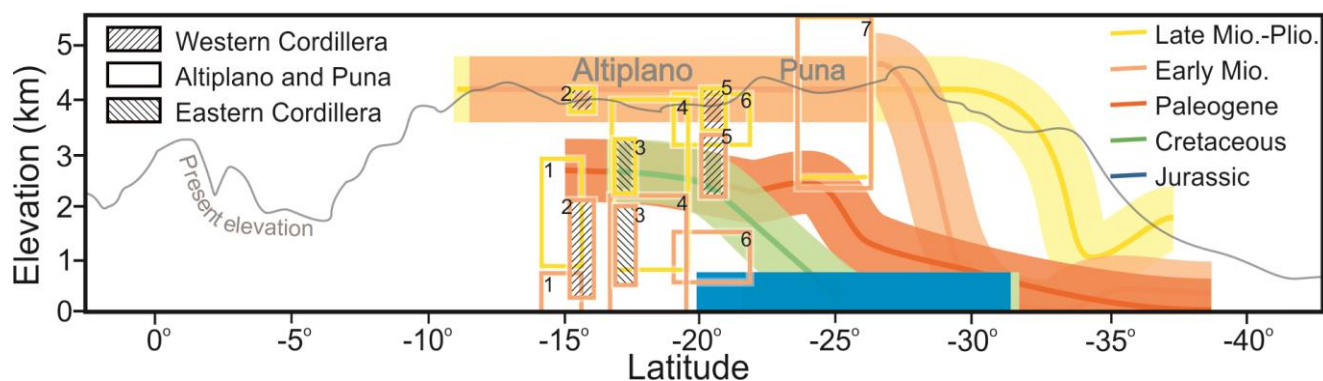


Figure 6 | Surface uplift of the Central and Southern Andes from Jurassic-present. Coloured lines are our inferred regional paleoelevation estimates for the Western Cordillera using our Sr-isotope plateau discriminant and SVZ calibration. Past plateau elevation is inferred to be similar to present day Western Cordillera elevations (4200 ± 516 m, mean CVZ volcano elevation ± 2 SD, using 37.5 km smoothing). Non-plateau paleoelevation estimates have lines set to a thickness representing 95% confidence (± 564 m). For general comparison, previously published paleoelevation estimates are shown in boxes, simplified to fit the same time intervals used in this study (1=ref. 24, 2=ref. 63, 3=ref. 23, 4=refs. 21,22, 5=ref. 65, 6= ref. 25, 7=ref. 18).